

Probing the photoionised outflow in the NLS1 Ark 564: An XMM-Newton view

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ABSTRACT

We present a detailed analysis of *XMM-Newton* X-ray observations of the Narrow line Seyfert-1 (NLS1) galaxy Ark 564 taken between 2000 and 2011. High-resolution X-ray spectroscopy is carried out on the resultant high signal-to-noise stacked spectrum. We find three separate photoionised warm absorbers outflowing at velocities unusually lower than typical NLS1s. Using recombination timescale estimates, improved constraints on the location of these clouds show they could be located beyond 4 pc from the central source. Our estimates of the outflow kinetics suggest that the AGN in Ark 564 is unlikely to affect the host galaxy in its current state but over typical lifetime of 10^7 years the ISM could be affected. The individual observations used here suggest the luminosity varies over weekly timescales and in addition we find evidence of gas response to changes in the ionising radiation.

Key words. galaxies: active – galaxies: nuclei – galaxies: Seyfert – galaxies: individual: Ark 564 – X-rays: galaxies

1. Introduction

Active Galactic Nuclei are among the brightest objects in the sky, spanning across 9 orders of magnitude in luminosity (Shang et al. 2011). The engine of this energy output is thought to be accretion onto a supermassive black hole (SMBH) at the centre of the host galaxy resulting in typical luminosities of $\sim 10^{42}$ erg s⁻¹ (Seyferts) to 10^{46} erg s⁻¹ (Quasars). In addition to a bright continuum, a plethora of absorption and emission features in the X-ray band are also a common feature and in several sources the observed spectral lines are blue-shifted by several 1000 km s⁻¹, indicating the presence of outflowing gas in the line of sight. One suggested explanation is that these outflows are produced by irradiation of the dusty gas torus structure (Antonucci 1993), which surrounds the SMBH and accretion disk (Krolik & Kriss 2001).

High resolution X-ray spectroscopy can be performed on nearby sources and this allows us to characterize both the environment as well as the energetics associated with ionised outflows from AGN. This is important in the context of feedback to the host galaxy, which is considered a solution to the galaxy luminosity function bright end problem (Silk & Mamon 2012). But since only about 10% of AGN are radio-loud (Calafut & Wiita 2015) it seems natural to consider kinetics of the radio-quiet sources such as Seyferts, which are a subclass of AGN found in the nearby universe. While in Seyfert 2 galaxies both the disk and black hole are obscured by dust (side-on view), in Seyfert 1's both these features are visible (top-down view) making them ideal candidates for studying outflows. In particular NLS1s show broad absorption troughs in the optical and X-ray and also exhibit strong Fe (II) lines (Osterbrock & Pogge 1985) allowing regions close to the central source to be studied. In many low-luminosity Seyfert galaxies partially ionised material or ‘warm-absorbers’ gives rise to

absorption features at energies around 1 keV. In the last two decades surveys have found warm-absorption in about 50% of nearby Seyferts (Nandra & Pounds 1994; Blustin et al. 2005). In recent years warm-absorbers have also been detected in a few Radio galaxies although the jet still remains the dominant feedback mechanisms in such AGNs (Torresi et al. 2012).

In this paper we attempt to characterise the physical structure of the NLS1 AGN Arakelian 564 (hereafter Ark 564) by making use of all *XMM-Newton* data on the source so far. Ark 564 is located at a redshift $z = 0.02468$ and is among the brightest sources in the nearby universe with a 2–10 keV flux $f_{2-10} \sim 10^{-11}$ erg s⁻¹cm⁻². We perform spectral analysis on the stacked spectrum in order to determine the ionisation and dynamical structure of the outflow. Ark 564 like several other NLS1s is already known to be a highly variable source best illustrated during the month long ASCA observation by Gliozzi et al. (2002), when it displayed non-linear behaviour. Given the timespan of our data we will look for long-term variability of the source and the resulting gas response.

Radio-quiet quasars are scaled up versions of Seyferts (Leipski et al. 2006) found at cosmological distances ($z > 0.1$). Estimating the mass loss in nearby AGN can provide order-of-magnitude estimates of the impact of outflows on host galaxy star-formation (Krongold et al. 2007). We will derive similar quantities and compare with other well known sources.

2. Observations and data reduction

The data were extracted using the *XMM-Newton* SAS software v13.5. Fluxed spectra with 0.01 Å wide bins were created for each RGS detector and each spectral order, and for each individual observation. Following the methods described by Kaastra et al. (2011), the four spectra were combined into

Table 1: Details of the *XMM-Newton* (RGS) observations of Ark 564. Hereafter, in this paper the sources will be called by the observation tags shown here.

Observation tag	Observation ID	Start time (UTC)		RGS X-ray exposure (s)
		yyyy-mm-dd	hh:mm:ss	
01	0006810101	2000-06-17	03:48:06	16962
02	0006810201	2000-06-17	08:46:32	22140
03	0006810301	2001-06-09	05:20:12	6944
04	0006810401	2001-06-09	07:25:45	15656
05	0206400101	2005-01-05	19:15:22	100630
06	0670130201	2011-05-24	05:56:05	59316
07	0670130301	2011-05-30	15:08:42	55753
08	0670130401	2011-06-05	22:56:32	62445
09	0670130501	2011-06-11	16:59:18	67098
10	0670130601	2011-06-17	04:16:50	60742
11	0670130701	2011-06-25	23:16:43	54611
12	0670130801	2011-06-29	06:48:05	58056
13	0670130901	2011-07-01	06:45:51	55747

one spectrum using the `RGS_fluxcombine` program, an auxiliary program of the `SPEx` software (Kaastra et al. 1996) version 2.06.00¹. The same program is used to produce the stacked total spectrum of Ark 564, and the optimised response matrices were produced using the `RGS_fmat` program. The details of the 13 *XMM-Newton* RGS observations are provided in Table 1. The average exposure time is about 50 ks. In order to obtain the best signal-to-noise ratio, the individual observations have been stacked together to produce a time-averaged spectrum discussed in Sect. 3.2.

3. Spectral Analysis

3.1. Source Spectral Energy Distribution

For the purpose of photoionisation modelling of the outflows, we determined the broadband spectral energy distribution (SED) of the ionising source in Ark 564 (Fig. 1). The UV and X-ray parts of the SED were constructed from the *XMM-Newton* OM photometric filters (UVW1, UVM2 and UVW2) and the EPIC-pn spectrum (0.3–10 keV).

In order to expand the energy coverage of the SED beyond that of *XMM-Newton* into lower and higher energies, we used archival flux measurements from the NASA/IPAC Extragalactic Database (NED). We extracted infrared flux measurements at 25, 60 and 100 micron from IRAS and a radio flux measurement at 2380 MHz from Arecibo. We also included a Suzaku flux measurement given over the 10–50 keV band. As the source becomes too faint at hard X-rays, we applied a cut-off at 400 keV to our continuum model, which is a typical cut-off value found in bright AGN eg. NGC 5548 (Ursini et al. 2015).

We determined the SED by applying a broadband AGN continuum model to the above data. We used the broadband continuum model discussed in Mehdipour et al. (2011, 2015), which is based on Compton up-scattering of the IR/optical/UV disk photons to X-ray energies in warm and hot coronae. The use of this model enables us to establish the continuum from infrared to X-ray energies, including the EUV part, which is important for photoionisation calculations.

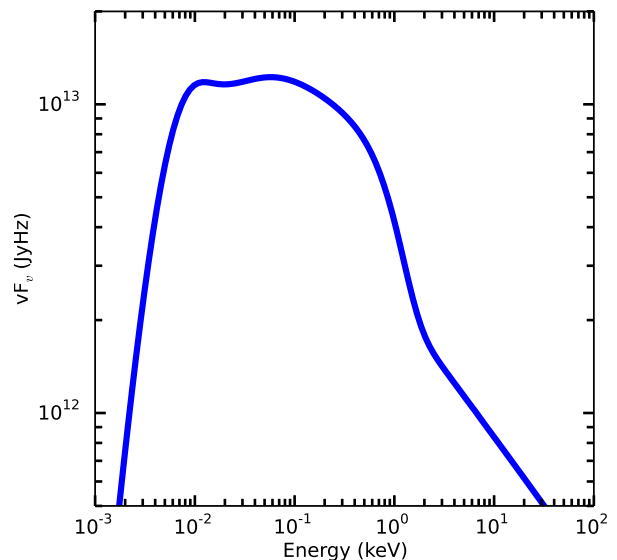


Fig. 1: Spectral Energy distribution of Ark 564 derived using the EPIC-pn and OM data of 2011 *XMM-Newton* observations.

In addition to correction for interstellar X-ray absorption and reddening in the Galaxy, we also corrected for reddening in the host galaxy of Ark 564. There are reports of substantial internal reddening in Ark 564. Thus, we adopted the colour excess $E(B - V) = 0.14$ reported by Crenshaw et al. (2002) to correct for host galaxy reddening in Ark 564, assuming the same dust extinction law as the Galaxy. In our galaxy, the colour excess is smaller at $E(B - V) = 0.03$ (Schlegel et al. 1998). To correct the data, we applied the reddening curve of Cardelli et al. (1989), including the update for near-UV given by O’Donnell (1994).

All spectra were modelled using the `SPEx` code, adopting a Λ -cosmology with $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. For the spectral analysis we use χ^2 statistics and the optimum data bin size was determined using Shannon binning.

¹ <http://www.sron.nl/spex>

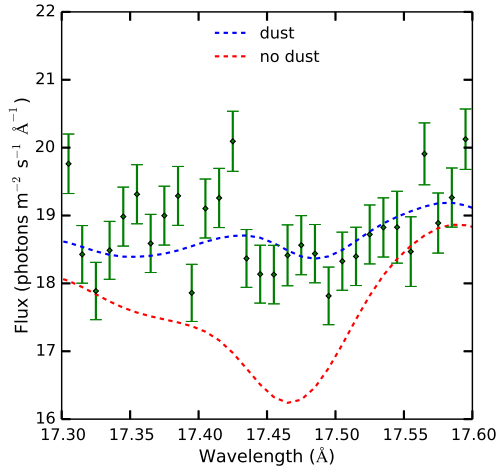


Fig. 2: Weakness of galactic neutral iron in gas form (red curve) in the line of sight to Ark 564 predicted by $N_H = 5.34 \times 10^{20} \text{ cm}^{-2}$ (Kalberla et al. 2005), suggests presence of Fe in dust form (blue curve) in our own galaxy.

Adopting this the data were binned with a redistribution function FWHM of $\Delta E/3$. The RGS resolution is 70 mÅ (Shannon FWHM ~ 50 points/Å) while our stacked spectrum has 100 points/Å, thus we have binned our data by a factor of 2.

3.2. Continuum Fitting

In previous studies, the continuum has usually been modelled with a steep power law of photon index ~ 2.5 and soft-blackbody components (Vignali et al. 2004). But others have also shown that the soft-part is not very well modelled with a simple black-body, there have been relativistic disk profiles as well as multiple black-body components in one fit (Papadakis et al. 2007). Taking a cautious approach we use spline interpolation to fit the basic continuum. A grid of 18 points equally spaced by 2 Å was used over the range 6–40 Å with an extended boundary to reduce errors due to sharp discontinuity at the edge of the RGS band.

For the Galactic interstellar X-ray absorption we used the *SPEX* *hot* model with $N_H = 5.34 \times 10^{20} \text{ cm}^{-2}$ in our line of sight towards Ark 564 (Kalberla et al. 2005). This is assumed to be a cold neutral absorber ($kT \sim 0.5$ eV) and clearly fits the O I Galactic oxygen line at 23.5 Å in the RGS spectrum. This was also identified earlier by Ramírez (2013) and Smith et al. (2008). However, the *hot* model also predicts absorption around 17.47 Å corresponding to neutral iron. The data do not show a strong signature here and it is likely due to Galactic dust. By freeing the atomic Fe abundance in the *hot* model and including iron in dust form (using the *amol* model in *SPEX* and component Fe_2O_3) we get a much better fit (see the blue line in Fig. 2) with an Fe_2O_3 column of $N_H = 3.36 \times 10^{15} \text{ cm}^{-2}$. This is consistent with other high-resolution X-ray spectra through the Galactic ISM, e.g. Pinto et al. (2013). It is not unlikely that the Galactic foreground medium has multiple temperature components and indeed additionally we notice O VII absorption at 21.6 Å which is well fitted with a second warmer *hot* model with a temperature ~ 0.15 keV and turbulence with $v_{\text{turb}} = 36 \pm 20 \text{ km s}^{-1}$. This is the $1s^2 \text{ } ^1S_0 - 1s2p \text{ } ^1P_1$ transition (Mewe et al. 1985).

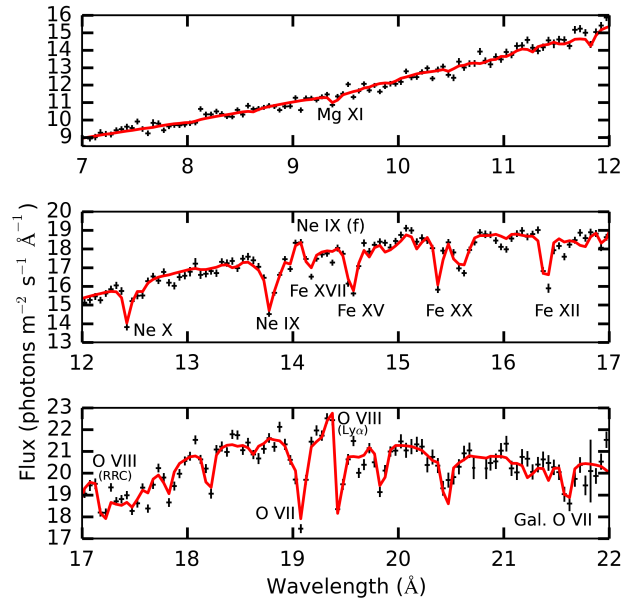


Fig. 3: Blow-up of the high resolution RGS spectrum of Ark 564 showing important emission and absorption lines between 7–22 Å as discussed in the text. The best-fit final full spectrum (7–38 Å) with residuals is shown in Fig. 5.

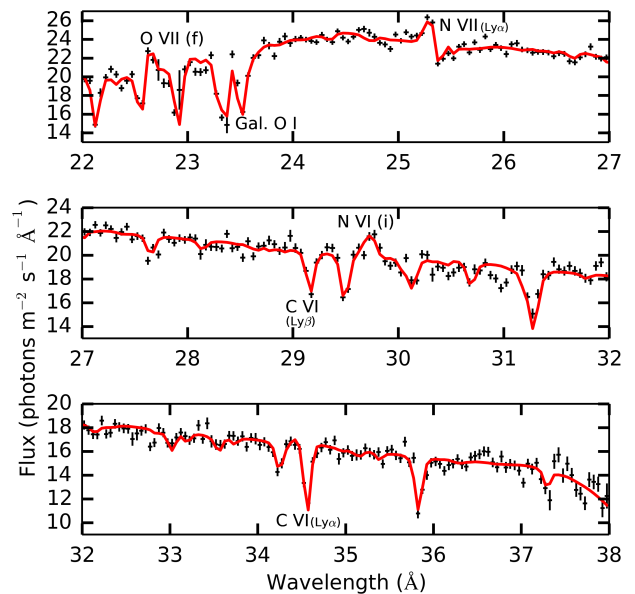


Fig. 4: Same as Fig. 3 but between 22–38 Å.

3.3. Emission lines

Figures 3 and 4 show zoomed-in sections of the main spectrum, highlighting the emission features. These were fitted with the *delta* and *vgau* models in *SPEX* which incorporate narrow emission lines with Gaussian broadening. Prominent lines are listed in Table 2 along with the broadening velocity σ .

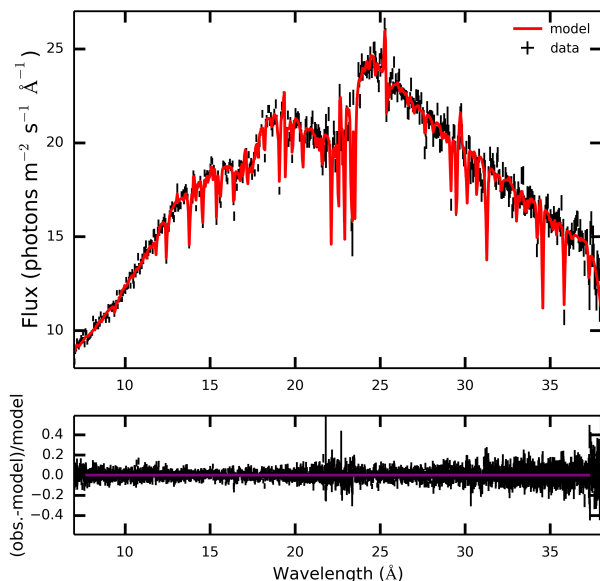


Fig. 5: Shown in black is the stacked *XMM-Newton* RGS high-resolution spectrum produced by combining all Ark 564 RGS observations to date. The final best-fit is shown in red and consists of galactic absorption, broad and narrow Gaussian emission lines, three phases of photoionised warm-absorbers all on a continuum modelled by spline interpolation. The lower panel shows the residuals (black) for this fit.

We infer three distinct zones the emission lines could originate from. The Ly α lines for C, N and O seem to be from a high-velocity/turbulence zone, while the two forbidden lines (O VII and Ne IX) show negligible outflow signature. In addition, the intercombination line of N VI is half as broadened as that of the Ly α lines. Smith et al. (2008) suggest that since signature of intercombination lines is an indication of high-density and since the N VI(i) and O VII(f) & Ne IX(f) seem to come from separate components this suggests that the faster component could also be denser. However, we note that for oxygen the derived density estimates from line ratios is likely unreliable due to self-absorption of the resonance and then the intercombination line (Mehdipour et al. 2015).

The narrow and broad emission lines are generally assumed to arise from a photoionised plasma, where in general the temperature is much smaller than the ionisation potential of the dominant ions in the plasma. In this case, we expect to see Radiative Recombination Continua (RRC). Candidates for RRC in our band include O VII, C V and Ne IX. While we do not detect carbon or neon RRC, there is clearly a feature around 17 Å which corresponds to the O VIII to O VII recombination. In addition we find a Doppler shift ($z_{\text{Dop}} = \frac{\Delta\lambda}{\lambda}$) at the source for this feature of $z_{\text{Dop}} = -2.43 \times 10^{-3}$ corresponding to a blueshift of about 800 km s $^{-1}$.

3.4. Relativistic Broad lines?

From the stacked spectrum two extremely broad asymmetric features seem apparent in the region covering 18–30 Å. We explore the possibility of these being broad relativistic emission lines originating from the O VIII and N VII Lyman alpha transitions.

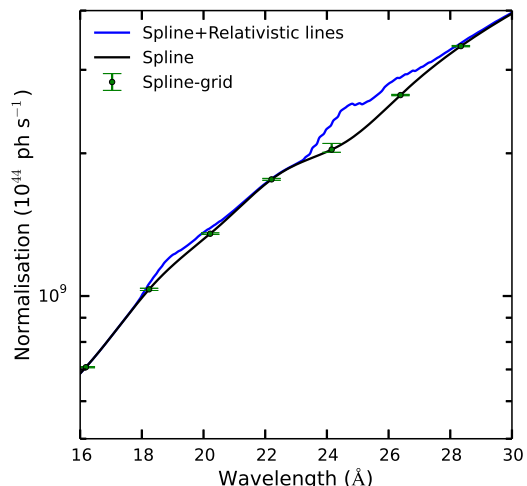


Fig. 6: The spline continuum with fitting for broad relativistic lines. The error-bars are insignificant as is illustrated in the blow-up of the relevant region: N VII (24.73 Å) and O VIII (18.94 Å) in the laboratory frame.

Relativistically broadened skewed lines result from a combination of gravitational redshift due to the deep potential around black-holes and relativistic beaming due to gas swirling at relativistic velocities (Fabian et al. 2002). There have been previous reports of broad Ly α lines for other sources such as MCG-6-30-15 and Mrk 766 (Branduardi-Raymont et al. 2001). We checked this broadened feature in the Ark 564 spectrum by modelling with a LAOR profile (Laor 1991) in SPEX. The best fit results for an inner radius of $10 \frac{GM}{c^2}$, consistent with a non-rotating black-hole, with the disk aligned at about 37°. The parameters are provided in Table 3 and including the possible broad relativistic lines at the O VIII and N VII Ly α energies improves $\Delta\chi^2 \sim 500$ for 1490 d.o.f. Fig. 6 shows the spline continuum with and without the two relativistic lines and though it would appear that the features are statistically significant (given the small error bars) we would like to point out that with a slightly higher, more powerlaw-like spline continuum in this band, the remaining residuals are of the order of a few percent. Recent calibration work by one of us (J.S.K.) shows that the RGS effective area has remaining residuals at a similar level of a few percent on scales of a few Å. We leave it open here whether the relativistic lines are real or serve to compensate for small calibration uncertainties.

3.5. Photoionisation modelling of absorption clouds

A preliminary search for absorption features was done using the SLAB model (Kaastra et al. 2002) in SPEX, which allows for ionic column densities to be chosen independently. This also provided us with an estimate of the outflow velocity of the absorbing gas. For a more realistic calculation we made use of *xabs* components in SPEX. The *xabs* model calculates the transmission of a slab of material, where all ionic column densities are linked through the CLOUDY (Ferland et al. 1998) photoionisation model. The parameters fitted for each *xabs* component are the ionisation parameter ($\xi = \frac{L_{\text{ion}}}{n(R)R^2}$), turbulence, outflow velocity and the column density with $n(R)$ defined as the hydrogen gas density at R which is the distance between the source and the absorber. We made use of the derived SED of Ark 564 (Sect. 3.1) in order to calcu-

Table 2: Narrow and Broad non-relativistic emission lines with line-flux as observed

Line	λ (observed) Å	λ_0 (rest) Å	λ_0 (lab.) Å	Broadening (σ) km s ⁻¹	Line-flux (observed) 10 ⁵⁰ ph s ⁻¹
O VII (f)	22.65±0.01	22.10±0.01	22.10	70 ⁺¹⁸⁰ ₋₇₀	0.89 ±0.08
Ne IX (f)	14.05±0.01	13.71±0.01	13.70	0 ±290	0.22 ±0.03
N VI (i)	29.76±0.01	29.04±0.01	29.09	540 ±150	1.00 ±0.16
O VIII Ly α	19.41±0.06	18.94±0.06	18.97	770 ±70	1.76 ±0.11
N VII Ly α	25.34±0.02	24.73±0.02	24.78	1026 ±130	2.33 ±0.20
C VI Ly α	34.54±0.03	33.71±0.03	33.74	950 ⁺³⁰⁰ ₋₄₇₀	1.27 ±0.38

Table 3: Summary of the spectral features (other than narrow emission lines) and best-fit parameters used to model the stacked spectrum of Ark 564 resulting in a final $\chi^2/\text{d.o.f.} = 5178/3034$.

Feature	Parameter	Status	Value
Galactic Absorption (cold phase)			
	nh, Column Density (10 ²⁴ m ⁻²)	frozen	5.34
	Temperature (10 ⁻⁴ keV)	frozen	5.0
	RMS Turbulence (km s ⁻¹)	thawn	21 ± 5
Galactic Absorption (warm phase)			
	nh, Column Density (10 ²³ m ⁻²)	thawn	2.5 ± 0.6
	Temperature (keV)	thawn	0.15 ± 0.01
	RMS Turbulence (km s ⁻¹)	thawn	36 ± 15
Radiative Recombination (O VIII → O VII)			
	Emission strength (10 ⁶⁴ m ⁻³)	thawn	4400 ± 400
	Temperature (10 ⁻³ keV)	thawn	9.5 ± 0.8
	Doppler shift (10 ⁻³)	thawn	-2.7 ± 0.6
	Doppler velocity (km s ⁻¹)	thawn	-800 ± 200
Broad Relativistic Lines			
	O VIII Ly α (10 ⁵⁰ ph s ⁻¹)	thawn	4.4 ± 0.6
	N VII Ly α (10 ⁵⁰ ph s ⁻¹)	thawn	21.0 ± 2.0
	Inner radius R_{in} (GM/c ²)	thawn	10 ⁺² ₋₇
	Emissivity index q	thawn	1.83 ± 0.05
	Inclination i	thawn	37° ± 0.5°

late the ionisation balance in the CLOUDY code and obtain $L_{\text{ion}} = 6.9 \times 10^{37}$ W. Here we assume Solar abundances (Lodders et al. 2009), however, since AGN are typically known to have high abundances in the elements C, N, O and Fe (Komossa & Mathur 2001) we also tested for non-solar abundances but did not find strong deviations from solar metal abundance ratios, a similar result as found in the case of Mrk 509 by Steenbrugge et al. (2011). Hence, we have assumed Solar abundances for Ark 564. We find that the best fit is achieved with three separate *xabs* components with equal spatial covering factor $f_{\text{cov}}=1$. These vary in ionisation as well as in their outflow signature. Table 4 ranks the three absorption phases identified by their ionisation parameter (ξ) and additionally we note that the highly ionised phase 3 produces most of the Fe and Ne lines. Compared with the outflow velocities for emission lines in Table 2, the absorbing gas seems to be present in weakly outflowing regions suggesting that the origin of the absorber and the emission lines is likely to be dif-

ferent. However, the OVII(f) does have broadening comparable to phases 2 and 3 so there could be a connection between these.

On the basis of the distinct ξ parameters that we find, it would appear that Ark 564 has three separate absorption components. To test this further in Fig. 7 we plot the pressure form of the ionisation parameter, $\Xi = L_{\text{ion}}/4\pi r^2 c n_{\text{H}} kT$, against the absorber temperatures ($\approx 10^5$ K) derived using *SPEx* with the SED from the 2011 (Fig. 1) observations. In Fig. 7 regions with positive gradient represent where gas is in photo-ionisation equilibrium and is stable against thermal perturbations while the negative slopes indicate unstable zones. Since at a given distance r , L_{ion} is independent of gas density, $\Xi \propto P_{\text{gas}}^{-1}$, and thus on such a plot, absorbers with a range of densities and temperatures can line up vertically if in pressure-equilibrium. This is considered to play a role in confining neighbouring outflowing clouds such as in NGC 985 where the absorbers are present in a multi-phase wind (Krongold et al. 2005). For Ark 564, it is clear that the three ab-

Table 4: The three warm absorber components found in Ark 564. Two of the gas components are outflowing at low velocities while the third phase is consistent with no outflow. The location of each phase has been constrained as discussed in Sect. 4.3.

Phase	Outflow velocity (km s ⁻¹)	Turbulence (km s ⁻¹)	Log ξ (10 ⁻⁹ Wm)	N _H (10 ²⁴ m ⁻²)	Log L _{abs} (W)	C _v	Location (pc)
Phase 1	-48 ± 15	130 ± 9	-0.25 ± 0.02	1.56 ± 0.08	37.0	0.03	80 ≤ r ≤ 74000
Phase 2	-53 ± 17	79 ± 4	1.37 ± 0.03	3.18 ± 0.12	36.2	0.17	7.5 ≤ r ≤ 864
Phase 3	0 ± 18	87 ± 5	2.38 ± 0.03	7.39 ± 0.39	35.6	- ^a	4.2 ≤ r ≤ 37

^a Phase 3 shows negligible outflow which would result in a non-physical covering factor, hence we ignore it in our calculations.

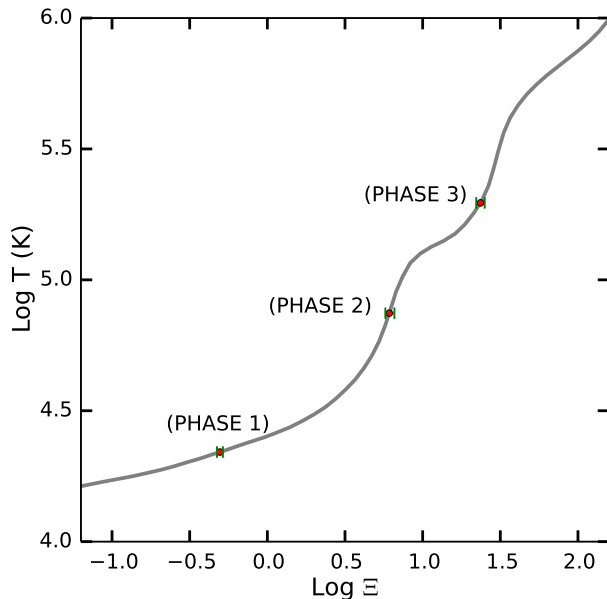


Fig. 7: Stability Curve with the positions indicated of the three warm-absorbers from our best fit for Ark 564. The absence of a region with negative slope on the S-curve indicates there are no unstable regions i.e. gas can exist in equilibrium throughout the curve. This is likely due to the steep soft-excess seen in Ark 564 which allows gas to cool efficiently by lowering the Compton temperature. (Marker size exaggerated to show against small error bars in green)

sorbers do not line-up on the stability curve and so are not in pressure-equilibrium. It is interesting to note that the kinetics of phases 1 and 2 are very similar with regards to the outflow velocities as compared to the negligible outflow in phase 3. Additionally, there is overlap in the locations of the absorbers (Sect. 4.3) from phases 1 and 2 so perhaps this suggests another mechanism by which these two zones are confined. Distinct ionisation components are also seen in other well studied sources. In NGC 5548 Steenbrugge et al. (2005) detect up to 5 components not in pressure-equilibrium yet with similar kinetics to each other pointing towards a single confined outflow, quite unlike our situation. Also, Mrk 509 (Ebrero et al. 2011) shows three distinct ionisation zones, although, on the S-curve the outflowing components are in pressure-equilibrium with each other while the third component, which was in fact found to be redshifted was not in equilibrium with its outflowing counterparts. For Ark 564 we also note that the S-curve does not have any unstable re-

gions which is likely due to the source having a steep soft X-ray spectrum which removes instabilities by lowering the Compton temperature of the gas, allowing it to cool more efficiently (Guilbert et al. 1983). Such behaviour has also been noted for other NLS1s such as I ZW 1 (Costantini et al. 2007).

4. Discussion

4.1. Comparison with previous spectroscopic studies

The data sets used in this paper have been studied separately before. Generally the features we report are similar to other works. We obtain similar column density and ionisation parameter to Ramírez (2013) who observed Ark 564 using Chandra LETGS. The analysis of the line at observed wavelength of 19 Å suggests this is from phase 2 and we get a slightly higher ionisation parameter of Log ξ = 1.34 to their Log ξ = 1.1 but very similar column density and line width. Smith et al. (2008) also show this line but do not discuss it. Giustini et al. (2015) using a different photoionisation code in xspec find similar features to us.

Previous works mostly find the best-fit model to be consistent with two separate phases of warm-absorbers. From the Ark 564 2005 observations, Papadakis et al. (2007) find two phases with Log ξ ~1 and 2, similar to the 2002 results from Matsumoto et al. (2004). Dewangan et al. (2007) using both EPIC and RGS data from 2005 report similar numbers and in addition find very high velocity outflows of up to 1000 km s⁻¹. Smith et al. (2008) performed spectroscopy on the stacked spectrum of data up to 2005 and although they assume continuum parameters as reported by Papadakis et al. (2007), they found the best-fit model to require three separate phases of absorption and not in pressure-equilibrium similar to the results presented in this paper.

4.2. Luminosity and Ionisation variability

The spectrum used in our analysis compiled using 13 observations over a period of about 10 years. Using the best-fit parameters from the high resolution stacked spectrum we can now look at the source during the individual observations. For each spectrum we are primarily interested in the gas response to changes in source luminosity and so we keep all best-fit parameters from the stacked data frozen except for the normalisation of lines and continuum as well as the ionisation parameter (ξ). The resulting set of parameters is shown in Table 5 and all spectra are fitted with $\chi^2/d.o.f.$ ~1.2. Based on this in Fig. 8a we plot the long term light-curve for Ark 564 where it is apparent that over this period the source seems to vary by a factor of 2. Unlike continuous monitoring surveys which allow analysis of evenly spaced time-intervals (e.g. Gliozzi et al. (2002)) here we have time-averaged

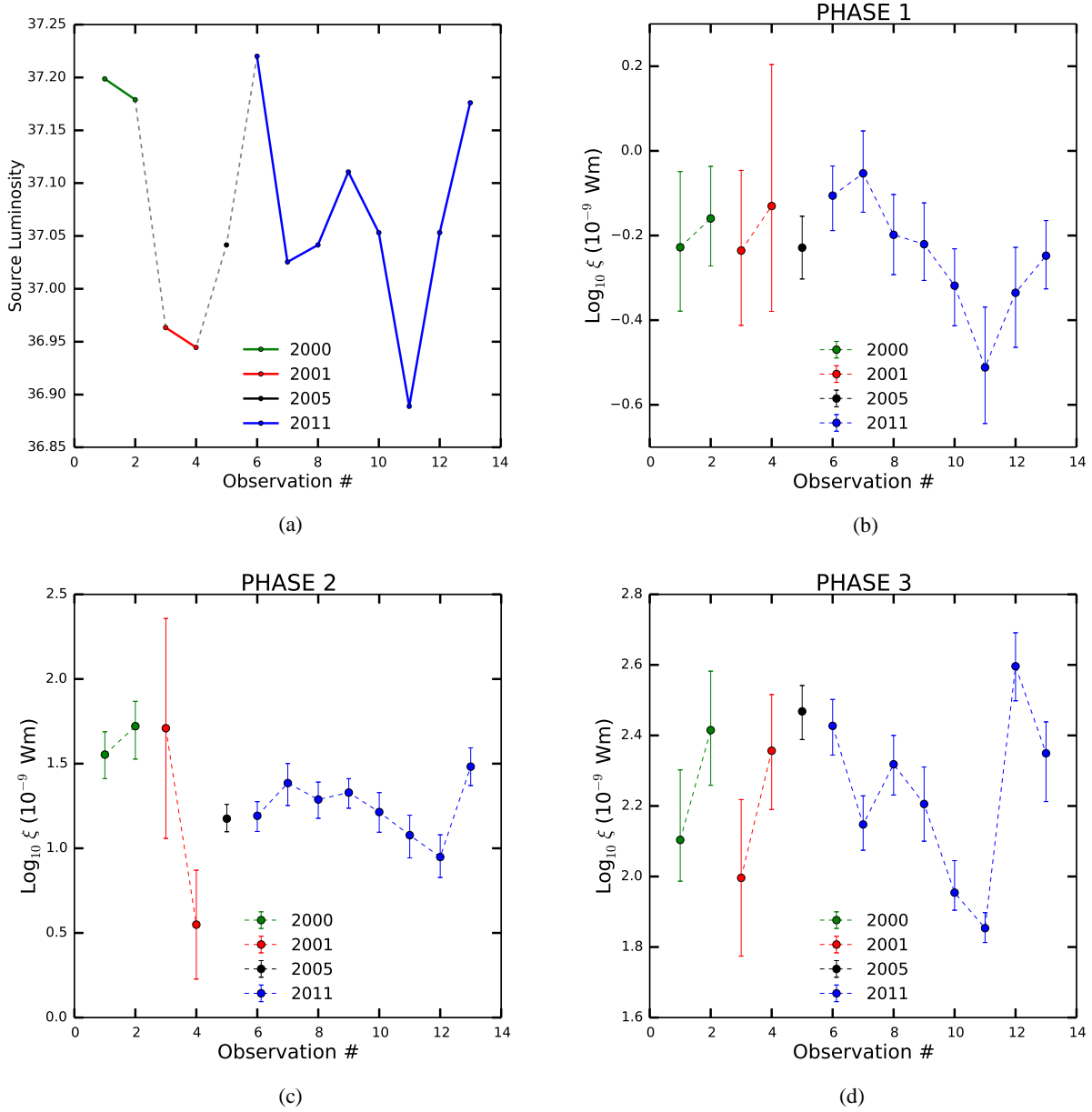


Fig. 8: (a) Based on the best-fit parameters from the stacked spectrum we derive luminosities for all the individual observations between 2000–2011. The individual data sets are highlighted and so the combined plot is not evenly spaced in time. Observation # are as in Table 1. (b), (c) & (d) Ionisation parameter (ξ) for the individual observations derived using stacked spectrum. Compared to (a) it seems ξ varies in response to changing source luminosity. The response time is related to the gas density so the component in phase 3 is possibly denser than the remaining two warm-absorbers.

observations taken over a decade. However, the 2011 data were taken every 6 days from May 2011 to July 2011 and so here we shall use this set to look for correlations. Additionally, we are interested in the gas response for which we use the ξ parameter as a proxy. Fig. 8(b–d) shows the variation in ionisation over all observations where at first glance it seems that during 2011 all three gas phases seem to be responding to the ionising luminosity. However, within the shown errors only the highest ionised phase (# 3) seems to mirror the light curves in Fig. 8a unlike the other two phases of warm-absorbers.

We can use recombination timescales to estimate the location of the warm-absorbers, the clouds of photoionised gas being radiatively driven out. Essentially, the response timescale to lumi-

osity variations can be used as a measure for the gas density as $\tau_{\text{rec}} \sim \frac{1}{\alpha_{\text{rec}} n_e}$ such that denser gas would respond faster to changes in source luminosity (Reynolds & Fabian 1995). If the gas density is high enough then a rise in luminosity should be followed by a rise in ξ . This could be instantaneous (extremely dense) or there could be a significant lag (low density). In Fig. 8(b–d) we plot ξ for the individual observations, derived by using the best-fit parameters from the stacked spectrum as described earlier. The three panels show the gas response in each phase over the 10 year period and visually it seems that the ionisation parameter was responding to the source luminosity during the 2011 campaign. To check this further in Fig. 9 we again plot the best-fit ξ parameter but now against the ionising luminosity for all in-

dividual observations to search for correlations. We find that in all three phases there is a weak correlation with an average Pearson coefficient of ~ 0.45 and p -value $\sim 10\%$ thus we can't reject null hypothesis. However, if in 2011 (evenly spaced data set) all phases change responding to source luminosity, this would indicate that the gas response time has to be less than or equal to ~ 6 days (an assumption we use to estimate the distances to the warm-absorbers).

4.3. Constraints on warm-absorber location

Since there are at least three independent absorbers, we can now estimate their locations, R , with respect to the source. By integrating the 2011 SED (Fig. 1), we can estimate the ionising luminosity, which between 1 and 1000 Rydberg gives $L_{\text{ion}} = 6.9 \times 10^{37}$ W. This can be related to the absorbing source by the definition of ξ (Sect. 3.5) and following Smith et al. (2008), we assume that the thickness (Δr) of any ionised gas phase has to be less than or equal to its distance (R) from the source or:

$$\frac{\Delta r}{R} \leq 1 \quad (1)$$

and since the neutral Hydrogen column density (N_{H}) can be related to the number density as:

$$N_{\text{H}} \sim n(R)C_{\text{v}}\Delta r \quad (2)$$

we can provide an expression for the upper limit of the gas cloud location as:

$$R \leq \frac{L_{\text{ion}}C_{\text{v}}}{\xi N_{\text{H}}} \quad (3)$$

with the NLS1 volume filling factor, C_{v} estimated following Blustin et al. (2005) for each phase by matching outflow momentum with scattered and absorbed radiation momentum giving:

$$C_{\text{v}} = \frac{(\dot{P}_{\text{abs}} + \dot{P}_{\text{scat}})\xi}{1.23m_p L_{\text{ion}} v^2 \Omega} \quad (4)$$

with the components defined in Appendix A and values listed in Table 4. Since phase 3 is consistent with negligible outflow we prefer not to average the remaining two covering factors but instead use the mean $C_{\text{v}} = 0.03$ for NLS1s as obtained by Blustin et al. (2005). Thus we obtain upper limits for the distances from the source: phase 1 = 74 kpc, phase 2 = 864 pc and phase 3 = 37 pc.

For a more robust estimate to the absorber distances we make use of the recombination time-scale, τ_{rec} . This defines how quickly the gas in the outflow is able to adjust to changes in ionisation and is related to the density n_{H} and recombination rate $\alpha_{\text{r}}(X_i)$ from ion X_{i+1} to ion X_i by:

$$\tau_{\text{rec}}(X_i) = \left(\alpha_{\text{r}}(X_i) n \left[\frac{f(X_{i+1})}{f(X_i)} - \frac{\alpha_{\text{r}}(X_{i-1})}{\alpha_{\text{r}}(X_i)} \right] \right)^{-1} \quad (5)$$

where $f(X_i)$ is the fraction of all atoms of the element in ionisation state X_i .

For each absorption phase, using the SPEX tool 'rec_time' we calculate the product $n_{\text{H}} \times t$ for the strongest lines (here Fe and O). Here, in principle, we should use ions with the highest concentrations but where τ_{rec} is negative i.e. the ion recombines to a lower state we use the next strongest absorption after the first positive τ_{rec} to avoid instability near turn-around in polarity. Then assuming that the fastest recombination would occur

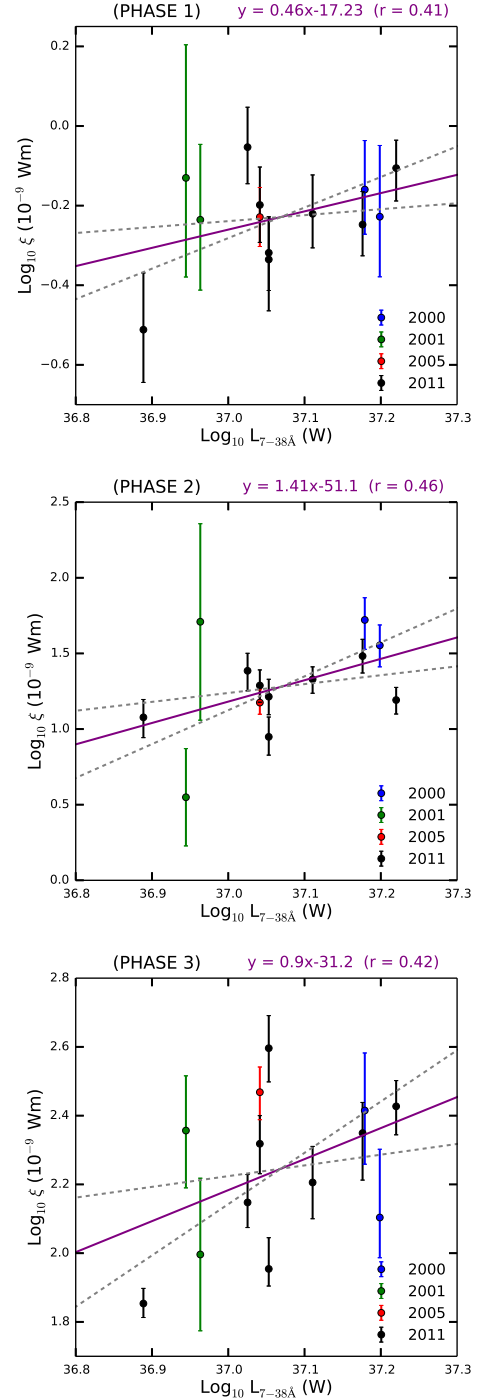


Fig. 9: Ionisation plotted against Luminosity for all Ark 564 RGS observations. The panels correspond to the three phases and the best-fit line (purple) and Error in the best-fit (grey) along with the Pearson coefficient r are also shown. Top: Phase 1 ($\xi \approx -0.25$, gradient: 0.46 ± 0.31); Centre: Phase 2 ($\xi \approx 1.37$, gradient: 1.41 ± 0.82); Bottom: Phase 3 ($\xi \approx 2.38$, gradient: 0.90 ± 0.59). It seems ξ and L are linked but in an imperfect correlation possibly due to sparse data for Ark 564.

on the shortest time-scale of observations ($\tau_{\text{obs}} \sim 6$ days) we can obtain a lower limit for n_{H} :

$$n_{\text{H}} \leq \frac{(n_{\text{H}} \times t)}{\tau_{\text{obs}}} \quad (6)$$

and then using $\xi = L/nr^2$, we obtain revised limits (Table 4) for the cloud locations with the innermost absorber being at about 4 pc from the source. Smith et al. (2008) constrained the warm-absorbers to be between 100 pc–1000 kpc. We therefore report distance estimates improved by nearly 2 orders of magnitude. However, as was noted earlier, during the 2011 observations ξ changes for all 3 phases (Fig. 8(b-d)) and the change is observed on the timescales of ~ 6 days (the sampling period of the 2011 observations). But since the data are sparse it is possible the changes could be even faster; evidence of this is the correlation between ξ and L which is imperfect (Fig. 9), the imperfections may point to the faster timescales. This suggests that the gas could be responding to luminosity changes in less than 6 days which would imply higher n_H and thus much lower distance estimates than those derived here.

4.4. Outflow kinetics

Using constraints on the location of the warm-absorbers we can now estimate the kinetics of the outflowing material. Following Crenshaw & Kraemer (2012) the mass outflow rate (\dot{M}_{out}) and Kinetic Luminosity, L_{kin} are given by:

$$\dot{M}_{\text{out}} = 4\pi\mu m_p N_H C_v r v_{\text{out}} \quad (7)$$

$$L_{\text{kin}} = 2\pi\mu m_p N_H C_v r v_{\text{out}}^3 \quad (8)$$

where we use the outflow velocity (v_{out}) as in Table 4. Again to provide conservative estimates we use the typical average volume filling factor for NLS1's of $C_v = 0.03$ similar to that obtained for phase 1 in Ark 564. Ignoring phase 3 (since it is consistent with negligible outflow), we find $\dot{M}_{\text{out}} \sim 0.1\text{--}2.0 M_{\odot} \text{ yr}^{-1}$ and $L_{\text{kin}}/L_{\text{bol}} \sim 0.0002\%\text{--}0.01\%$ for phase 1 and phase 2 respectively. We note that in their analysis of 23 AGN Crenshaw & Kraemer (2012) use a global covering factor of 0.5 for their estimates which would scale our numbers by two orders of magnitude. Given that the warm-absorbers in the case of Ark 564 are not co-located we prefer to use the average covering factor for this source.

4.5. Outflow strength and impact on host galaxy

The outflow velocities for Ark 564 are lower than are generally expected of NLS1s, given the high accretion rate relative to Eddington Luminosity (Boroson 2002). A number of factors could be responsible for the weak outflows. Firstly, if the outflows are radiation-pressure driven, the intrinsic variability of the source and thus of the accretion rate could naturally force material at different strengths. Secondly, orientation of the source relative to the observer could play a role where the highest-velocity components will be detected if the outflowing gas is perfectly in the line of sight and so it follows that at any deviation from this angle only the transverse component would be seen. Ramírez (2013) also find similar weak outflows in Ark 564 and suggest that this component could belong to the base of the wind in the accretion disk comparing it to the situation with NGC 4051 which is likely to be oriented at an angle of $\delta \sim 30^\circ$ (Krongold et al. 2007). In our analysis if at all the N VII and O VIII relativistic lines are statistically significant ($\Delta\chi^2 \sim 500$ for 1490 d.o.f.) we can thus support this argument as the LAOR profile predicts a disk at inclination angle of $37^\circ \pm 0.5^\circ$.

Ark 564 does not seem to have extreme mass outflow rate and kinetic luminosity, with a maximum $L_{\text{kin}}/L_{\text{bol}} \sim 0.01\%$. Our estimates are very similar to those derived using the

Chandra 2008 data analysed by Gupta et al. (2013). Moreover, Blustin et al. (2005) collated high-resolution spectroscopy results for 23 AGN and found the median $\dot{M}_{\text{acc}} \sim 0.04 M_{\odot} \text{ yr}^{-1}$ and $\dot{M}_{\text{out}} \sim 0.3 M_{\odot} \text{ yr}^{-1}$ which would suggest that Ark 564 has kinetics of a very typical Seyfert. In order for AGN to impact their host galaxies, models require between $L_{\text{kin}}/L_{\text{bol}} \sim 0.1\%$ (Hopkins & Elvis 2010) and $\sim 5\%$ (Di Matteo et al. 2005) and so it would appear that in its current state there is no significant feedback from the AGN to its host environment in Ark 564. However, these ionised outflows are believed to be long-lived matching the typical AGN lifetime of $\sim 10^7$ years during which the warm-absorbers could travel out to a few kpc and deposit up to $10^{54} \text{ erg s}^{-1}$ even with weak outflows such as observed for Ark 564. This is only an order of magnitude smaller than typical energies required for heating the ISM to $T \sim 10^7 \text{ K}$ and affect star-formation (Krongold et al. 2007). Lastly, while the upper limit to the location of the phase 1 absorber (74 kpc) does suggest it might be sustained by processes different than the ones responsible for phase 2, the fact that both these absorbers have similar kinetics lends further support to the idea that ionised outflows could be long-lived and thus could affect the host galaxy over typical AGN lifetime.

5. Summary

Ark 564 is a well studied source across different wavelengths and here we performed high-resolution X-ray spectroscopy on the combined data set from all *XMM-Newton* observations of this source. We determined the SED using a broadband continuum model for AGN and carried out photoionisation modelling on it. We detect Gaussian-broadened emission lines from three distinct zones: C, N and O Ly α ($\sigma \sim 900 \text{ km s}^{-1}$), N VI intercombination (i) ($\sigma \sim 500 \text{ km s}^{-1}$) and O VII & Ne IX forbidden (f) ($\sigma \sim 100 \text{ km s}^{-1}$). Significant presence of (i) and (f) relative to resonance lines also suggests photoionisation equilibrium (PIE) and so we used the *xabs* model to calculate transmission through a slab of material ionised by the central source and detect three phases of warm-absorbers with different ionisation parameters (-0.25 to 2.38). Also, these gas phases are not in pressure equilibrium and are not co-located, with the highest ionised phase possibly beyond 4 pc from the source. We also report two possible broad relativistic lines, though the RGS calibration uncertainties around the same wavelengths cast doubt on their presence. Using results from the stacked spectrum we provide best-fit parameters for the individual observations and searched for variability of luminosity and gas response to this. We find that the ionisation parameter seems to follow changes in luminosity, although not in a fully correlated way. Though the outflow velocities found here were weak, we made estimates on the kinetics of outflowing gas and find that in its current state the AGN in Ark 564 is unlikely to disrupt the host galaxy although over the typical lifetimes of active galaxies enough energy can be deposited into the ISM such that star formation can be affected.

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APPENDIX A

Following Blustin et al. (2005) we assume that the momentum of the outflow matches the sum of the momentum of the absorbed and scattered radiation. The basic equations used to estimate the volume filling factor are then as follows:

$$C_v = \frac{(\dot{P}_{\text{abs}} + \dot{P}_{\text{scat}})\xi}{1.23m_p L_{\text{ion}} v^2 \Omega} \quad (9)$$

with the ionising luminosity $L_{\text{ion}} = 6.9 \times 10^{37}$ W for Ark 564. The AGN solid angle is taken as $\Omega \sim 1.6$. To calculate the absorbed luminosity we applied our *xabs* parameters to the 2011 SED in order to obtain the transmission of each warm-absorber. Thus,

$$L_{\text{abs}} = \frac{\sum Flux_{\text{abs}}}{\sum Flux_{\text{not-abs}}} \times L_{\text{ion}} \quad (10)$$

where the summation is over all energy bins. This gives the expression for absorbed momentum as:

$$\dot{P}_{\text{abs}} = \frac{L_{\text{abs}}}{c} \quad (11)$$

For the scattered radiation momentum we use the optical depth ($\tau_T = \sigma_T N_H$) of the absorber with column density N_H and Thomson cross-section σ_T to obtain:

$$\dot{P}_{\text{scat}} = \frac{L_{\text{ion}}}{c} (1 - e^{-\tau_T}) \quad (12)$$

Table 4 lists the L_{abs} for phases 1 and 2 which both show outflows. Note that in this scheme phase 3 is closest to the source and so phase 1 is the outermost absorber. Also, since Phase 3 does not show any outflow we can not estimate a physical volume filling factor for this particular absorber unlike the other two mentioned above.

APPENDIX B

Table 5 on the following page presents the best-fit parameters obtained for the individual observations as discussed in Sect. 4.2. This was achieved by freezing all best-fit parameters from the stacked spectrum except for the flux normalisation and ionisation parameter (ξ).

Table 5: Best fit for individual spectra from 2000-2011 as discussed in Sect. 4.2. All spectra are fitted with $\chi^2/d.o.f.$ ~ 1.2

Param	# 01	# 02	# 03	# 04	# 05	# 06	# 07	# 08	# 09	# 10	# 11	# 12	# 13
Log ξ^a (Phase 1)	-0.23 ± 0.13	-0.16 ± 0.10	-0.24 ± 0.20	$-0.13^{+0.34}_{-0.23}$	-0.25 ± 0.07	-0.16 ± 0.10	-0.10 ± 0.09	-0.18 ± 0.09	-0.26 ± 0.08	-0.35 ± 0.09	-0.50 ± 0.15	-0.34 ± 0.12	-0.25 ± 0.10
Log ξ^a (Phase 2)	1.56 ± 0.10	1.73 ± 0.13	1.71 ± 0.65	0.55 ± 0.29	1.25 ± 0.07	1.21 ± 0.09	1.41 ± 0.10	1.36 ± 0.09	1.34 ± 0.07	1.24 ± 0.10	1.07 ± 0.13	0.95 ± 0.12	1.50 ± 0.10
Log ξ^a (Phase 3)	2.07 ± 0.12	2.41 ± 0.20	1.99 ± 0.20	2.36 ± 0.15	2.41 ± 0.08	2.43 ± 0.08	2.12 ± 0.07	2.29 ± 0.08	2.22 ± 0.11	1.95 ± 0.06	1.85 ± 0.05	2.60 ± 0.10	2.35 ± 0.10
O VII (f) ^b	$0.3^{+0.7}_{-0.3}$	2.4 ± 0.6	1.1 ± 0.9	0.8 ± 0.6	0.9 ± 0.3	0.6 ± 0.4	1.3 ± 0.4	0.4 ± 0.3	7.7 ± 0.3	1.0 ± 0.4	1.0 ± 0.3	1.1 ± 0.4	0.9 ± 0.4
Ne IX (f) ^b	0.8 ± 0.3	0.3 ± 0.2	0.8 ± 0.4	0.6 ± 0.2	0.3 ± 0.1	0.4 ± 0.2	0.5 ± 0.1	0.2 ± 0.1	0.3 ± 0.1	0.3 ± 0.1	0.4 ± 0.1	0.3 ± 0.2	0.2 ± 0.2
N VII Ly α ^b	$0.3^{+1.1}_{-0.3}$	1.6 ± 1.1	3.6 ± 1.7	2.8 ± 1.4	2.4 ± 0.4	2.6 ± 0.6	2.3 ± 0.5	2.4 ± 0.5	2.8 ± 0.5	2.2 ± 0.5	2.9 ± 0.7	2.9 ± 7.4	3.5 ± 0.9
N VI (i) ^b	$0.2^{+1.0}_{-0.2}$	2.6 ± 0.8	1.7 ± 1.1	1.5 ± 0.8	1.3 ± 0.4	1.2 ± 0.6	1.1 ± 0.5	1.4 ± 0.5	1.2 ± 0.5	0.8 ± 0.5	0.9 ± 0.4	0.9 ± 0.5	1.3 ± 0.6
O VIII Ly α ^b	1.8 ± 0.7	2.8 ± 0.7	1.7 ± 1.0	2.7 ± 0.7	1.4 ± 0.3	1.3 ± 0.4	1.7 ± 0.3	1.8 ± 0.3	2.1 ± 0.3	2.0 ± 0.3	1.5 ± 0.3	1.3 ± 0.4	2.1 ± 0.4
C VI Ly α ^b	2.2 ± 1.7	$0^{+1.3}$	$0^{+1.5}$	2.2 ± 2.2	$0.4^{+0.8}_{-0.4}$	$0.1^{+1.0}$	2.7 ± 1.1	1.9 ± 1.1	$43.0^{+0.6}_{-43.0}$	1.3 ± 1.1	1.2 ± 1.2	1.1 ± 1.1	3.1 ± 1.5
O laor ^c	12 ± 5	10 ± 4	20 ± 6	2^{+3}	3 ± 2	2^{+3}	8 ± 2	7 ± 2	6 ± 2	1^{+2}	5 ± 2	8 ± 2	12 ± 3
N laor ^c	1 ± 1	0^{+16}	35 ± 21	15 ± 15	12 ± 6	18 ± 9	10 ± 8	14 ± 8	20 ± 8	8 ± 8	12 ± 8	30^{+10}_{-1}	36 ± 10

^a Ionisation parameter in 10^{-9} Wm.^b Non-relativistic emission normalisation in 10^{50} ph s⁻¹.^c Broad relativistic line normalisation in 10^{50} ph s⁻¹.